Isotopic and Petrographic Study of the Lonely Ridge Granodiorite, Nilsen Plateau, Antarctica.

by

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Abstract

The Lonely Ridge Granodiorite is found on the Nilsen Plateau, which is located just south of the Amundsen Glacier in the central Transantarctic Mountains. The time of crystallization based on the Rb-Sr whole rock isochron method has been reported as approximately 620 m.y. ago. (Faure et al.) Subsequent to crystallization, the rock was subjected to a period of high pressure metamorphism resulting in intensive deformation. Evidence for this is found in thin sections containing strained biotite and quartz showing undulatory extinction, and an overall cataclastic texture.

A date of 476 m.y. was calculated for biotite using an assumed initial $^{87}Sr/^{86}Sr$ ratio of 0.704. This date represents the time elapsed since biotite last cooled to the temperature at which it can retain radiogenic ^{87}Sr, following a metamorphic event. An analysis of feldspar suggests lack of isotopic homogenization among the minerals.

The results of this study do not confirm the Rb-Sr date of 850 m.y. of McClelland.

Introduction

The Nilsen Plateau is located in the central Transantarctic Mountains between 86°and 86°30'S, and 158°to 160°W, just south of the Amundsen Glacier. The geology includes a Precambrian basement complex comprised of granite intrusives, metavolcanics, and metasedimentary rocks unconformably overlain by flat lying upper Paleozoic to lower Mesozoic sedimentary rocks, which were intruded by Jurassic dikes and sills. (McClelland.)

Field studies were conducted on the Nilsen Plateau during the 1963-64 austral summer by members of the Ohio State University Institute of Polar Studies. McClelland investigated the basement complex along the western escarpment of the plateau. He reported the results of his studies in an unpublished manuscript, in which it is stated that the Lonely Ridge Granodiorite is pretectonic and intruded sedimentary rocks during Precambrian time, at least 850 m.y. ago. He also states that regional deformation and metamorphism causing the foliation of these rocks occured approximately 470 m.y. ago. These interpretations are based on Rb-Sr and K-Ar age determinations made on biotite separated from a sample of the Lonely Ridge Granodiorite which was collected near the center of the pluton, away from any exposed contacts with younger intrusives and in a zone where cataclastic textures were least pronounced. This was done to minimize argon and strontium loss due to thermal effects. The age determination of the biotite by the Rb-Sr

method was 846±35 m.y. and by the K-Ar method was 472±10 m.y. The Rb-Sr date is uncommon for the Transantarctic Mountains. Most reported isotopic dates range from 450 to 550 m.y. (Craddock, 1970). The K-Ar date of McClelland lies within the usual range.

The purpose of this study was to employ isotopic and petrographic techniques in order to determine the crystallization and cooling history of the Lonely Ridge Granodiorite. The results will be compared to those of McClelland to see if a conclusion about his uncommonly high Rb-Sr date can be obtained.

Geology of the Nilsen Plateau

The basement complex of the Nilsen Plateau consists of three major plutons, forming a composite batholith made up of medium to coarse grained granodiorites and quartz monzonites. McClelland referred to these plutonic units as the Lonely Ridge Granoliorite, the South Leuco Quartz Monzonite, and the Cougar Canyon Quartz Monzonite. The Lonely Ridge Granodiorite is believed to be pretectonic, and is intruded by the other 2 plutons, which are syntectonic. Bordering the batholith on both sides are metavolcanic rocks of the Wyatt Formation, which have been intruded by quartz monzonite, and the La Gorce Formation, a slate-metagraywacke sequence now in the greenschist facies. (Mirsky,1969)

The flat lying, sedimentary rocks are the equivalent of the Beacon Rocks of southern Victoria Land, and overlie the basement unconformably. These include a basal tillite overlain by non-marine fluvial and coal-bearing strata consisting mainly of sandstones and siltstones. These rocks were intruded by dolerite sills and dikes, ranging from less than a meter to 300 meters in thickness.

Two periods of faulting have affected the basement rocks of the Nilsen Plateau. Many shear zones within the Lonely Ridge Granodiorite suggest that these units also contain parallel faults that are probably contemporaneous with the first period of faulting. The second episode affected the sedimentary rocks as well as the basement complex. (McClelland)

Description of the rock used for dating

The sample used in the analyses was collected by Douglas McClelland during the 1963-64 season.

Thin section description

The rock is holocrystalline and hypidiomorphic granular, with grain sizes ranging from nearly submicroscopic to 6 millimeters in length. The rock has been intensely sheared, as evidenced by undulatory extinction in quartz and biotite, the presence of ragged grain boundaries, and a general cataclastic texture. Many grains are bent, others are fragmented and extensive alteration of biotite and plagioclase is evident.

The following modal analysis is based on visual estimation.

Biotite	20-25%	Accessories
Quartz	30-35%	Sphene
Plagioclase	30-35%	Apatite
Epidote	2-3%(secondary)	Microcline
Chlorite	(secondary)	Hornblende
Muscovite	(secondary)	
Kaolinite	(secondary)	

Biotite - The grain size ranges from nearly sub-microscopic to 3.5mm. in length, the majority being about 1 millimeter. Most crystals are xenoblastic due to intense deformation and metamorphic reactions that have taken place in the system. The biotite is heavily strained, as shown by its undulatory extinction and some kink banding. Replacement by chlorite, muscovite, quartz, and plagioclase is common. Epidote occurs at the grain boundaries between plagioclase and biotite.

Quartz - Grains range from a fraction of a millimeter up to 6 mm. in the long direction. The grains occur as shapeless masses that have been extensively deformed and broken. Some of the fine, broken grains have rehealed to form larger masses, and much quartz occurs in fractures throughout the rock.

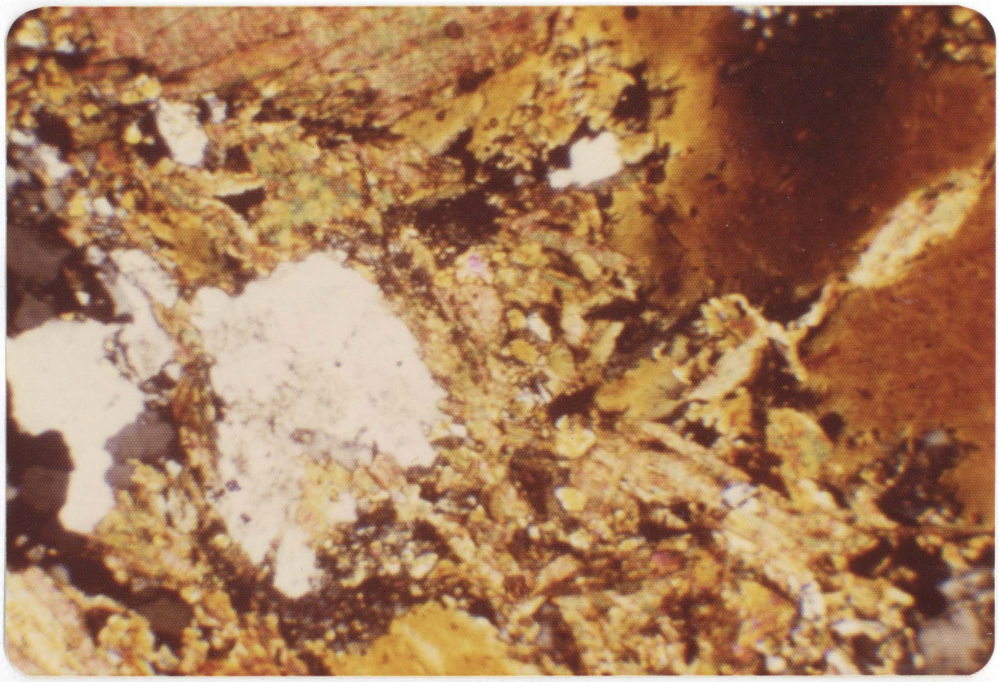
Plagioclase - Grains vary from tiny cataclastic fragments a fraction of a millimeter in length, to 4mm. long. The crystals are hypidioblastic to xenoblastic depending on the extent of alteration. Polysynthetic twinning is ubiquitous, but commonly obscured by extensive alteration to kaolinite and epidote, which invade the crystals preferentially through twin planes. Some of the crystals show oscillatory zoning which is sometimes very well displayed by secondary kaolinite forming between zones.

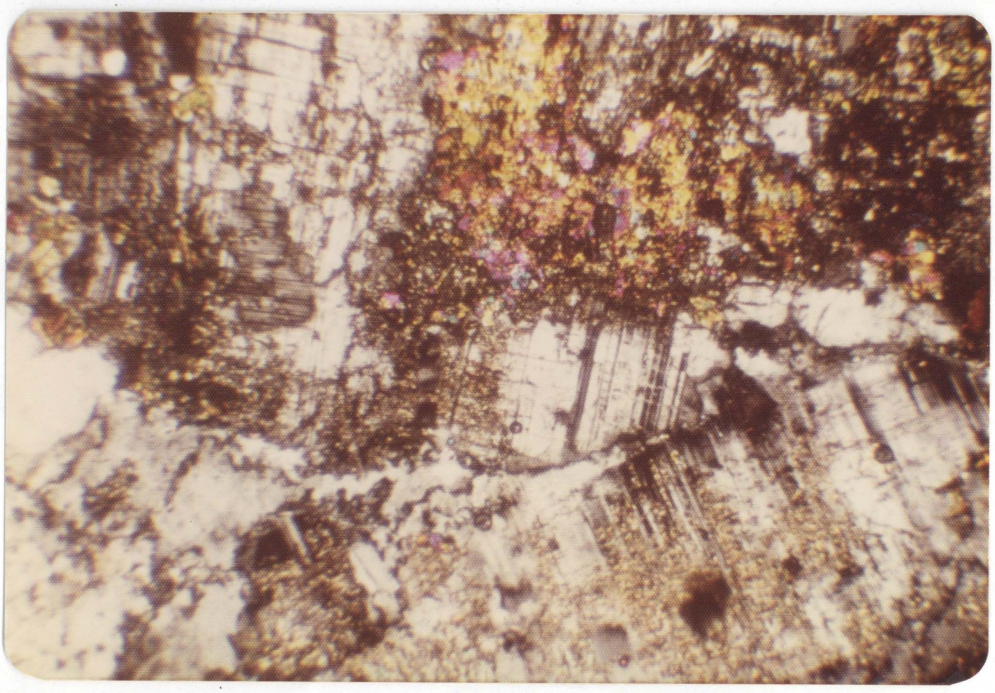
Alteration Products - Epidote, Kaolinite, Chlorite, Muscovite.

The chlorite replaces biotite, whereas epidote and kaolinite are alteration products of plagioclase. Muscovite is also found replacing biotite preferentially along cleavage cracks in places where the biotite is bent. Some of the replacement may be from metamorphic reactions in the system, as opposed to alteration.

Summary - Apparently this rock is a metamorphosed granodiorite. This is suggested by bent crystals of biotite showing undulose extinction, and the cataclastic texture. This suggests high pressure metamorphism with little or no recrystallization.

One anomalous crystal was observed, and is suspected to be staurolite, which would suggest some high temperature metamorphism.





Some of the above mentioned features can be seen in these photomicrographs.

Analytical Procedures

The whole rock was crushed and sieved to a -60 +120 mesh. The powder was passed through a Frantz Isodynamic Separator to obtain a magnetic and non-magnetic fraction. This procedure was repeated 3 times on the magnetic fraction, at continously decreasing magnetic fields, so as to eliminate the weakly or non-magnetic contaminants, and to improve magnetic purity. This yielded a magnetic component consisting of almost pure biotite, and a non-magnetic fraction made up of mainly quartz and sodic plagioclase. A portion of the non-magnetic fraction was crushed to -200 mesh, and a 3 gram sample was compressed into a pellet with a boric acid backing, for an X-ray fluorescence analysis of Rb and Sr concentrations.

A Diano Corporation XRD-6 air path spectrometer with a Molybdenum tube, a LiF analyzing crystal and a scintillation detector was used. Intensities were measured for 200 seconds at SrKα and RbKα radiation peaks at 2θ values of 35.85° and 37.99° respectively. Three baseline intensities were measured for 100 seconds at 2θ values of 35.20°, 36.50° and 38.58°, and MoKα Compton-scattered radiation was measured for use as a matrix correction at 30.00° 2θ for 100 seconds. (Reynolds, 1963)

A monitor (48R3) was run once before and after three consecutive runs on the feldspar pellet, to reduce the effects of drift in the instrument. The net Sr and net Rb values were divided by the MoKα radiation values and were then multiplied by a correction factor, f, to yield corrected values for (Sr/Mo)

by compensating for the drift in the XRF. (Figure 1) The corrected values, $(Rb/Mo)_c$ and $(Sr/Mo)_c$ were then used to calculate the concentrations of Rb and Sr in the sample by means of the following calibration equations:

$$Sr = 610.468\ R + 0.039 \qquad R = \left(\frac{Sr}{Mo}\right)_c$$

$$Rb = 816.345\ R + 0.038 \qquad R = \left(\frac{Rb}{Mo}\right)_c$$

These equations were obtained from separate analyses of the standard rocks of the U.S: Geological Survey.(Flanagan,1973)

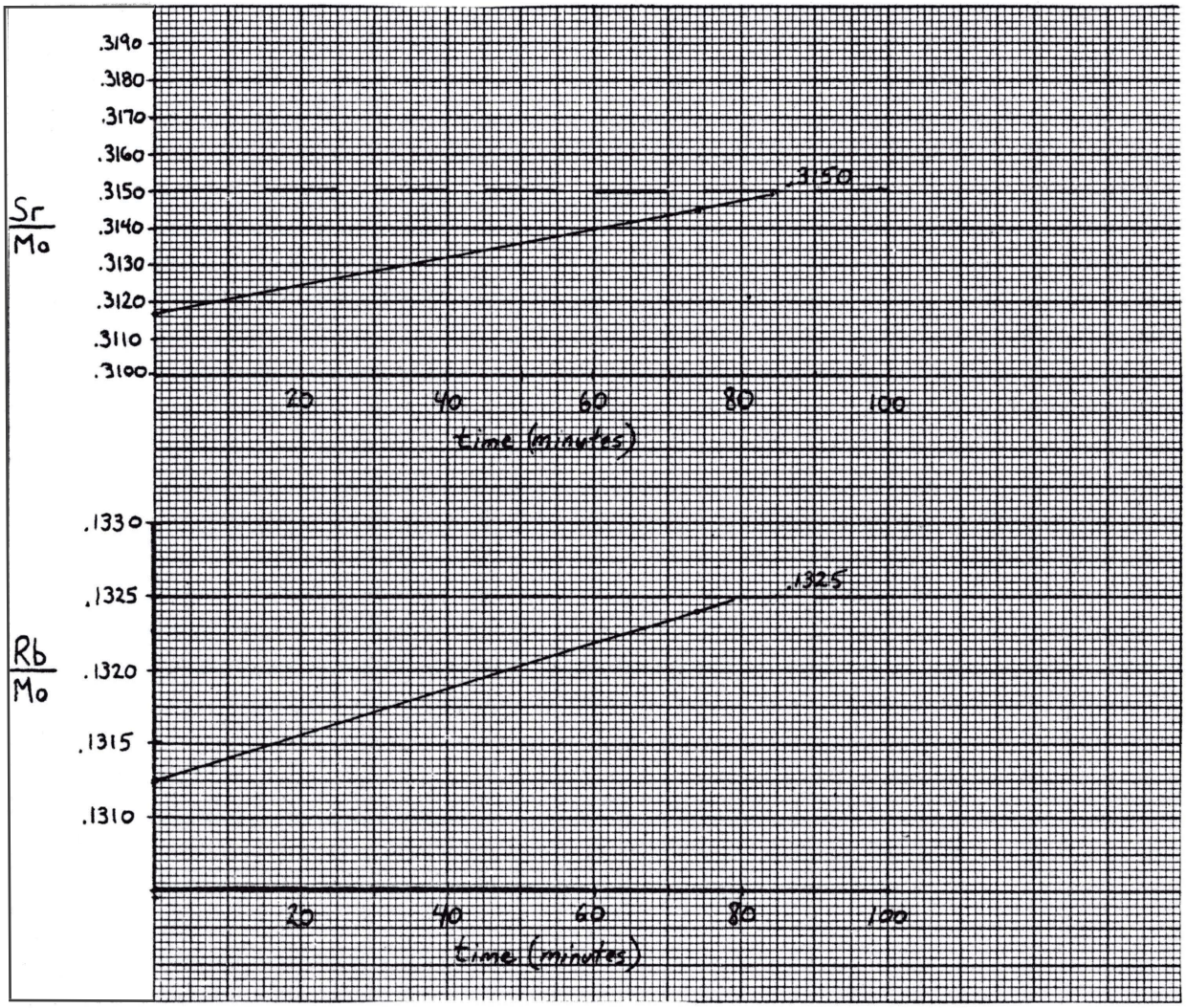


Figure 1

Monitor 48R3 was used to calculate a correction factor to compensate for drifting values in the XRF. 48R3 $\left(\frac{Sr}{Mo}\right) = .3150$, 48R3 $\left(\frac{Rb}{Mo}\right) = .1325$. The measured values of $\frac{Rb}{Mo}$ and $\frac{Sr}{Mo}$ for the

monitor before and after 3 consecutive runs on feldspar are plotted above. At any time t, if the monitor varies from its known $\frac{Sr}{Mo}$ or $\frac{Rb}{Mo}$ values, it can be multiplied by a factor, f, to correct it to its known value. The correction factor can be determined for any time t by dividing the known $\frac{Rb}{Mo}$ or $\frac{Sr}{Mo}$ value by the measured $\frac{Rb}{Mo}$ or $\frac{Sr}{Mo}$ at that time. The f values decrease as $\left(\frac{Sr}{Mo}\right)_{meas.}$ or $\left(\frac{Rb}{Mo}\right)_{meas.}$ approach their known values. The f values are multiplied by $\frac{Sr}{Mo}$ or $\frac{Rb}{Mo}$ values to obtain corrected values for the samples.

The $^{87}Sr/^{86}Sr$ ratio was determined on both the feldspar and the biotite by the use of a mass spectrometer. The two samples were prepared individually in the following manner. A 0.5 gram portion of the samples were dissolved in a 5:1 solution of HF and H_2SO_4 acids. The solution was then heated to evaporate excess HF. The solutions were placed into ion exchange columns with a ^{89}Sr tracer added, and were eluted with 2.2N HCl. The Sr fraction was identified by the activity of the ^{89}Sr tracer and was collected in a series of 15 ml. polyethylene beakers. In both cases, thirteen beakers of the solution were collected and tested for ^{89}Sr radiation by the use of a Geiger counter. The 2 beakers with the highest activity were combined and evaporated to dryness. Perchloric acid was added to the samples to remove organic residue, and then a small drop of the liquid was evaporated on the tantalum filament of the mass spectrometer to be analyzed for the $^{87}Sr/^{86}Sr$ ratios.

Isotope Dilution

Isotope dilution methods were used to determine the concentrations of Rb and Sr in the biotite. In this method, the concentration of an element is measured by adding a "spike" of known concentration whose isotopic composition has been changed by enrichment of one of its naturally occuring isotopes. The sample to be analyzed contains an unknown concentration of the element whose isotopic composition is known. When a known amount of sample is mixed with a known amount of spike, the isotopic composition of the mixture can be used to calculate the amount of the element in the sample(Faure,1977). The isotopic composition of the mixture is determined by analysis

on a mass spectrometer.

Sr determination

To determine the concentration of strontium, accurately weighed portions of biotite sample and ^{86}Sr spike were placed in a teflon dish, and the biotite was dissolved. The $^{86}Sr/^{88}Sr$ ratio of this mixture was then measured on the mass spectrometer. The following equation was used to convert the measured $^{86}Sr/^{88}Sr$ ratio to a ratio of total Sr atoms in the sample to total Sr atoms in the spike:

$$\frac{^{86}Sr}{^{88}Sr} = \frac{Ab_N^{86} \cdot N + Ab_s^{86} \cdot S}{Ab_N^{88} \cdot N + Ab_s^{88} \cdot S}$$

where N= total Sr atoms in sample, S= total Sr atoms in spike, Ab_N^{86} = abundance of ^{86}Sr in sample, Ab_N^{88} = abundance of ^{88}Sr in sample, Ab_s^{86} = abundance of ^{86}Sr in spike, and Ab_s^{88} = abundance of ^{88}Sr in spike. This equation was solved for (N/S)atomic, which is then converted to a weight ratio by multiplying by the factor:

$$f = \frac{\text{At. Wt. Sample Sr}}{\text{At. wt. Spike Sr}}$$

because the atomic weight of Sr in a sample varies with the amount of accumulated radiogenic ^{87}Sr. The converted weight ratio,(N/S)weight is then solved for N, the weight of Sr in the biotite, by substituting the known value for S which was previously determined by a spike calibration analysis. The

interpretive data and the calculations are as follows:

	Spike Sr	Normal Sr (biotite)
Ab ^{86}Sr	.97643	.09782
Ab ^{88}Sr	.01686	.81622
Atomic Weight	85.9493 amu.	87.60792 amu.
Concentration	4.756 µg/g	_____
Sample weight	5.2852 g.	_____

$$\left(\frac{^{86}Sr}{^{88}Sr}\right)_m = \frac{.09782\ N + .97643\ S}{.81622\ N + .01686\ S}$$

$$\frac{^{86}Sr}{^{88}Sr} = 1.0592 \pm .0239 \quad \text{(from Sr ID)}$$

$$1.0592 = \frac{.09782\ N + .97643\ S}{.81622\ N + .01686\ S}$$

$$.86454\ N + .01786\ S = .09782\ N + .97643\ S$$

$$.76672\ N = .95858\ S$$

$$\left(N/S\right)_{atomic} = \frac{.95858}{.76672} = 1.25023$$

$$f = \frac{\text{At. Wt. Sr (biotite)}}{\text{At. Wt. Sr (spike)}} = \frac{87.60792}{85.9493} = 1.01929$$

$$\left(N/S\right)_{weight} = 1.25023 \times 1.01929 = 1.27434$$

$$S_w = 5.2852\ g. \times 4.756\ \mu g/g = 25.1364\ \mu g$$

$$N_w = 1.27434 \times 25.1364 = 32.03232\ \mu g\ Sr$$

As a measure of the contamination introduced by sample processing, "blank" analyses have been made for Rb and Sr, using all the usual glassware, ion exchange columns, spike solutions, etc. No sample was added to the blank so that the resulting calculation for the weight of sample Rb or Sr is a measure of the contamination that has occurred, and is subtracted from the concentration. The most recent blank analysis yielded 0.06.

Sr blank correction

$$Sr = 32.03232 - 0.06 = 31.97232\ \mu g$$

$$Sr\ concentration = \frac{31.97232}{Sample\ Weight}$$

$$Sample\ Weight = \frac{2.8466\ g.}{250\ ml.} \times 50\ ml. = 0.56932\ g.$$

$$Sr\ concentration = \frac{31.97232\ \mu g\ Sr}{0.56932\ g.\ sample} = 56.16\ \mu g/g\ Sr$$

$$= 56.16\ ppm\ Sr$$

Rb determination

The determination of Rb concentration by the isotope dilution method was similar to the method just described for Sr. The following equation was used to convert the $^{87}Rb/^{85}Rb$

ratio measured on the mass spectrometer to the ratio of Rb atoms in the sample and spike.

$$\left(\frac{^{87}Rb}{^{85}Rb}\right)_m = \frac{Ab_N^{87} \cdot N + Ab_S^{87} \cdot S}{Ab_N^{85} \cdot N + Ab_S^{85} \cdot S}$$

	Spike Sr	Normal Rb(biotite)
Ab ^{87}Rb	.9918	.27855
Ab ^{85}Rb	.0082	.72144
Atomic Weight	86.8928 amu.	85.4678 amu.
Concentration	7.90 μg/g	_____
Sample Weight	4.7785 g.	_____

With calculations similar to those for Sr, and a similar blank correction, the Rb concentration obtained was 333.62 ppm.

Results and Interpretations

The results of all analyses are given in the table below.

	Biotite	Feldspar
Sr (ppm)	56.16	197.94
Rb (ppm)	333.62	49.80
Rb/Sr	5.9405	.25159
$^{87}Rb/^{86}Sr$	17.3266	.733807
$^{87}Sr/^{86}Sr$	.82153	.7170
$^{87}Sr/^{86}Sr$	.11985	.11922

The Rb-Sr mineral dates can be calculated for the feldspar and biotite using the above data and the following equation, which can be derived from the law of radioactivity (Faure, 1977).

$$\frac{^{87}Sr}{^{86}Sr} = \left(\frac{^{87}Sr}{^{86}Sr}\right)_o + \frac{^{87}Rb}{^{86}Sr}\left(e^{\lambda t}-1\right)$$

In this equation, t equals the time at which the minerals last became a closed system with respect to radiogenic ^{87}Sr; $\left(^{87}Sr/^{86}Sr\right)_o$ is an assumed initial ratio based on analyses of Sr derived from the mantle. The symbol lambda, λ, is a decay constant for ^{87}Rb, which has a value of $1.42 \times 10^{-11} y^{-1}$. Now we may calculate mineral dates by solving equation 1 for t, as follows:

$$t = \frac{1}{\lambda} \ln\left[\frac{\frac{^{87}Sr}{^{86}Sr} - \left(\frac{^{87}Sr}{^{86}Sr}\right)_o}{\frac{^{87}Rb}{^{86}Sr}} + 1\right]$$

Biotite:

$$t = \frac{1}{1.42 \times 10^{-11} y^{-1}} \ln\left[\frac{.82153 - .704}{17.3266} + 1\right]$$

$$= \frac{1}{1.42 \times 10^{-11} y^{-1}} \ln\left[1.0067832\right] = 4.7608 \times 10^{8} y. \approx 476 m.y.$$

Feldspar:

$$t = \frac{1}{1.42 \times 10^{-11} y^{-1}} \ln\left[\frac{.7170 - .704}{.733807} + 1\right] = 1.2367 \times 10^{9} y. \approx 1{,}236 m.y.$$

If the mineral dates from one rock are in agreement, they are said to be "concordant." In that case the mineral dates would also be likely to agree with the whole rock date. This would indicate that the minerals remained closed systems after initial crystallization, and that there was no post-crystallization "event" to cause the minerals to gain or lose radiogenic ^{87}Sr.

Looking back now at the dates calculated for the minerals, we see that the biotite and feldspar dates bracket the 620 m.y. age of crystallization by a considerable margin (Figure 2). The date btained for biotite is reasonable in that it may mark the time of reequilibration of strontium in the rock after metamorphism, and that it is in agreement with K-Ar date of McClelland. The biotite begins to retain radiogenic ^{87}Sr at approximately 300°C, which is termed the "blocking temperature" of the mineral; so approximately 476 million years ago, biotite could have once again became a closed system after isotopic reequilibration of strontium caused by a metamorphic event. This is quite feasible for the biotite results, but we must now turn to the feldspar, which yielded an anomalously high date. One would expect that the minerals in a rock would become isotopically homogenized following a metamorphic event (Figure 3).

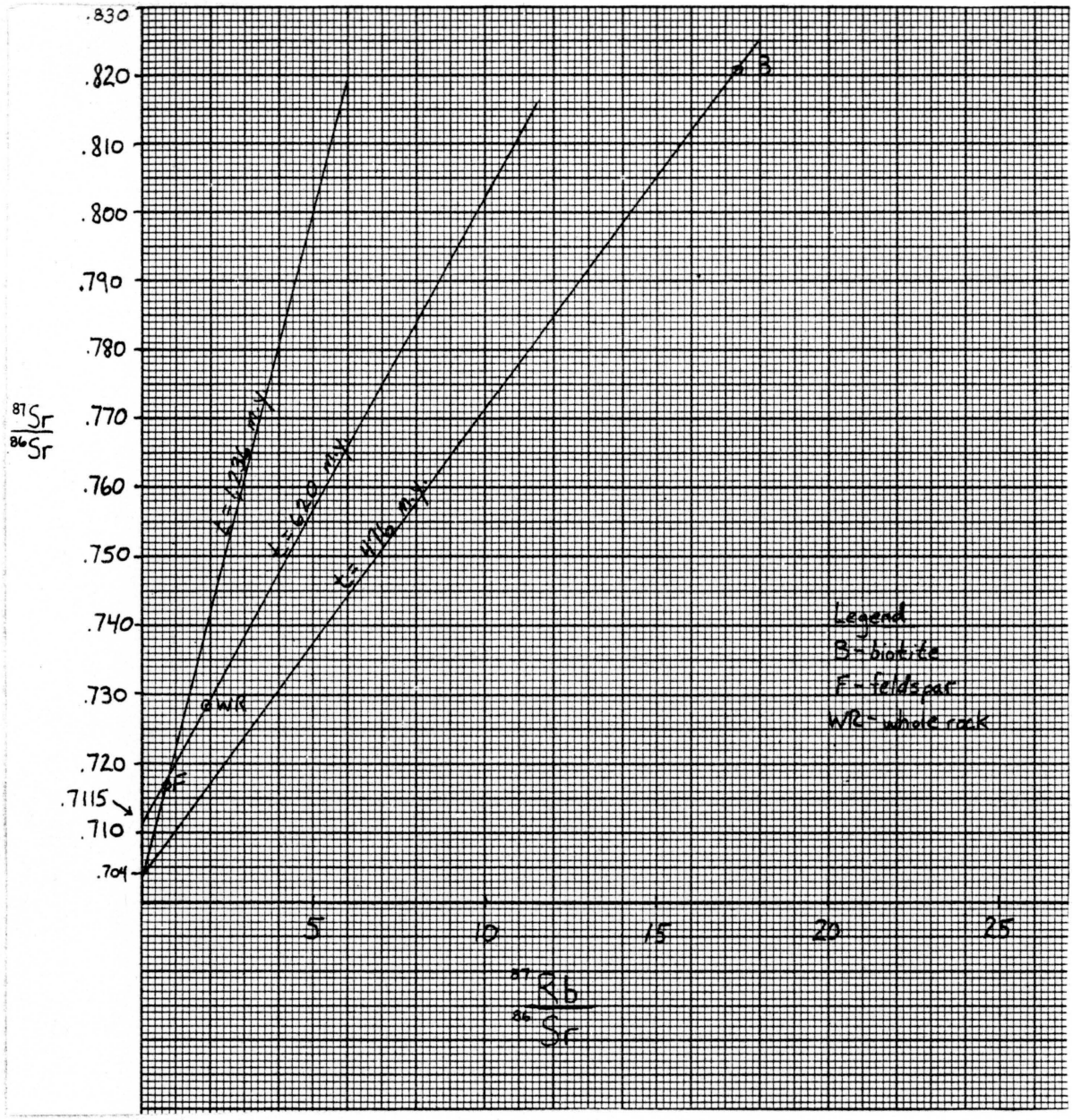


Figure 2

The mineral dates are discordant when calculated using an assumed initial $^{87}Sr/^{86}Sr$ ratio of 0.704; and bracket the age of crystallization of the rock. The whole rock had $^{87}Sr/^{86}Sr$ = 0.7284 and $^{87}Rb/^{86}Sr$ = 1.946

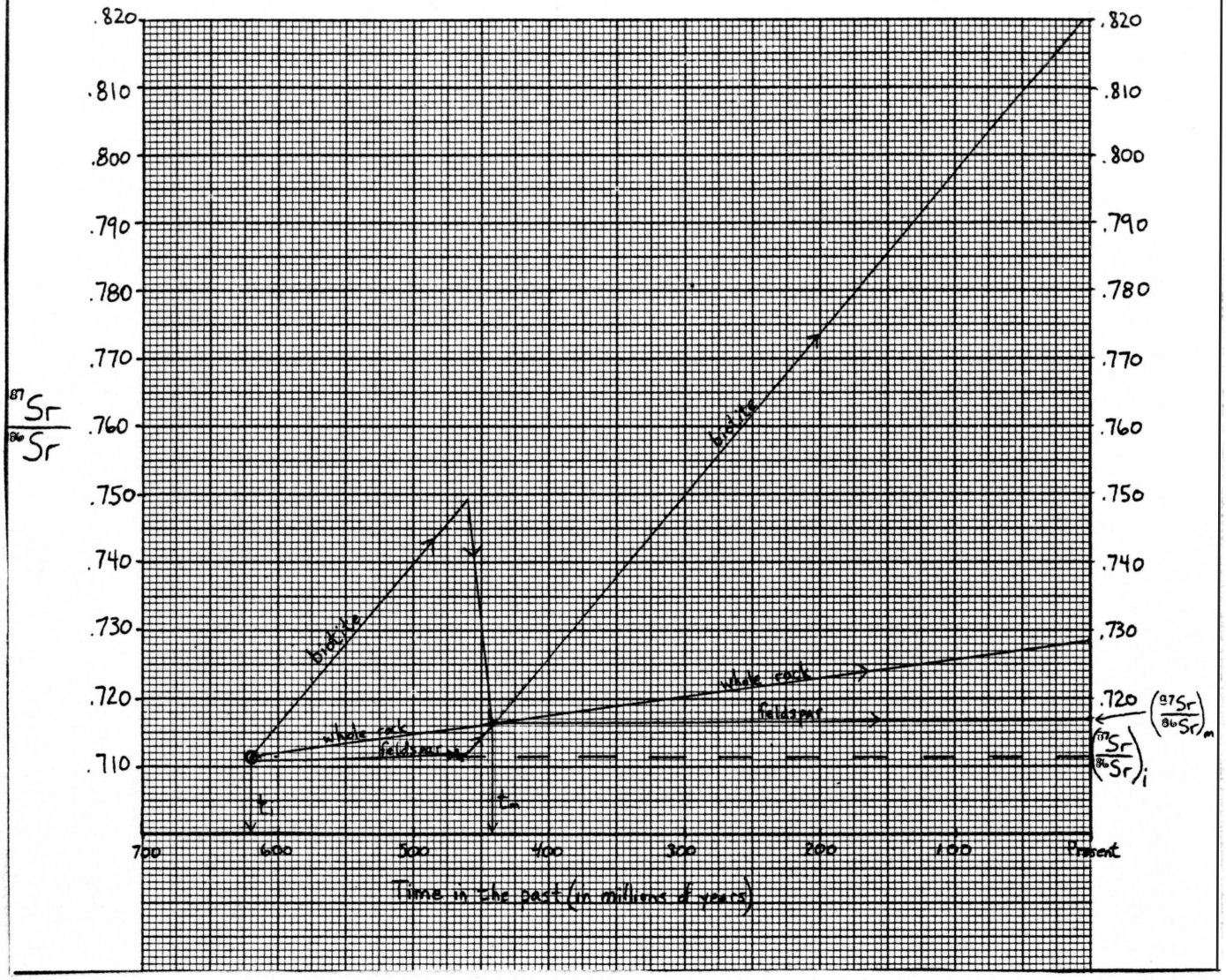


Figure 3

This illustrates the evolution of strontium in a rock that crystallized t_i years ago, at which time the isotopic composition of strontium in all minerals was $\left(^{87}Sr/^{86}Sr\right)_i$. The minerals evolve along straight line paths determined by their $^{87}Rb/^{86}Sr$ ratios. When the temperature was increased, the Rb rich phases lost radiogenic ^{87}Sr and their $^{87}Sr/^{86}Sr$ ratios decreased until they became identical to that of the whole rock. The radiogenic ^{87}Sr lost by the Rb rich phases entered

the Sr rich phases, and their $^{87}Sr/^{86}Sr$ ratios increased until they were also equal to that of the whole rock. At this stage strontium in the rock was isotopically homogenized such that all minerals again had the same $^{87}Sr/^{86}Sr$ ratio equal to $\left(^{87}Sr/^{86}Sr\right)_m$. The temperature eventually decreased enough for the minerals to become closed systems again at t_m, then the $^{87}Sr/^{86}Sr$ ratios increased to the present at rates determined by their $^{87}Rb/^{86}Sr$ ratios. This is based on the assumptions that the whole rock remained a closed system and that the minerals achieved complete isotopic homogenization following metamorphism. (After Faure, 1977)

A large error is introduced into the calculations by assuming an inappropriate initial $^{87}Sr/^{86}Sr$ ratio. Since the dates for feldspar and biotite are "discordant", it is reasonable to assume that this could indeed be the case. Since the biotite has a large $^{87}Sr/^{86}Sr$ ratio, the effects of an inappropriate initial ratio are almost negligible. The feldspar on the other hand has a relatively small $^{87}Sr/^{86}Sr$ ratio and is therefore highly dependent on the assumed initial ratio. To emphasize this point, the dates for feldspar and biotite were recalculated using an arbitrarily chosen initial ratio of .708. The results yielded biotite = 461 million years and feldspar = 864 million years. This slight adjustment varied the biotite date by only 15 m.y., while the feldspar date was changed by 373 m.y. It is obvious then that the feldspar date is an extremely sensitive function of the assumed initial ratio.

If we plot the feldspar and biotite on a graph with coordinates $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$, it becomes possible to draw a straight line through these 2 points (Figure 4). It now becomes important to point out that equation 1 is an equation of a straight line in the form $y = b+x(m)$. This means that the slope of the line is equal to $(e^{\lambda t} - 1)$. We can calculate the slope of the line using the coordinates of the two points.

$$m = \text{slope} = (e^{\lambda t} - 1) = \frac{\left(\frac{^{87}Sr}{^{86}Sr}\right)_B - \left(\frac{^{87}Sr}{^{86}Sr}\right)_F}{\left(\frac{^{87}Rb}{^{86}Sr}\right)_B - \left(\frac{^{87}Rb}{^{86}Sr}\right)_F}$$

where B = biotite and F = feldspar

$$\text{slope} = \frac{.82153 - .7170}{17.32662 - .733807} = \frac{.10453}{16.59279} = 0.00629972$$

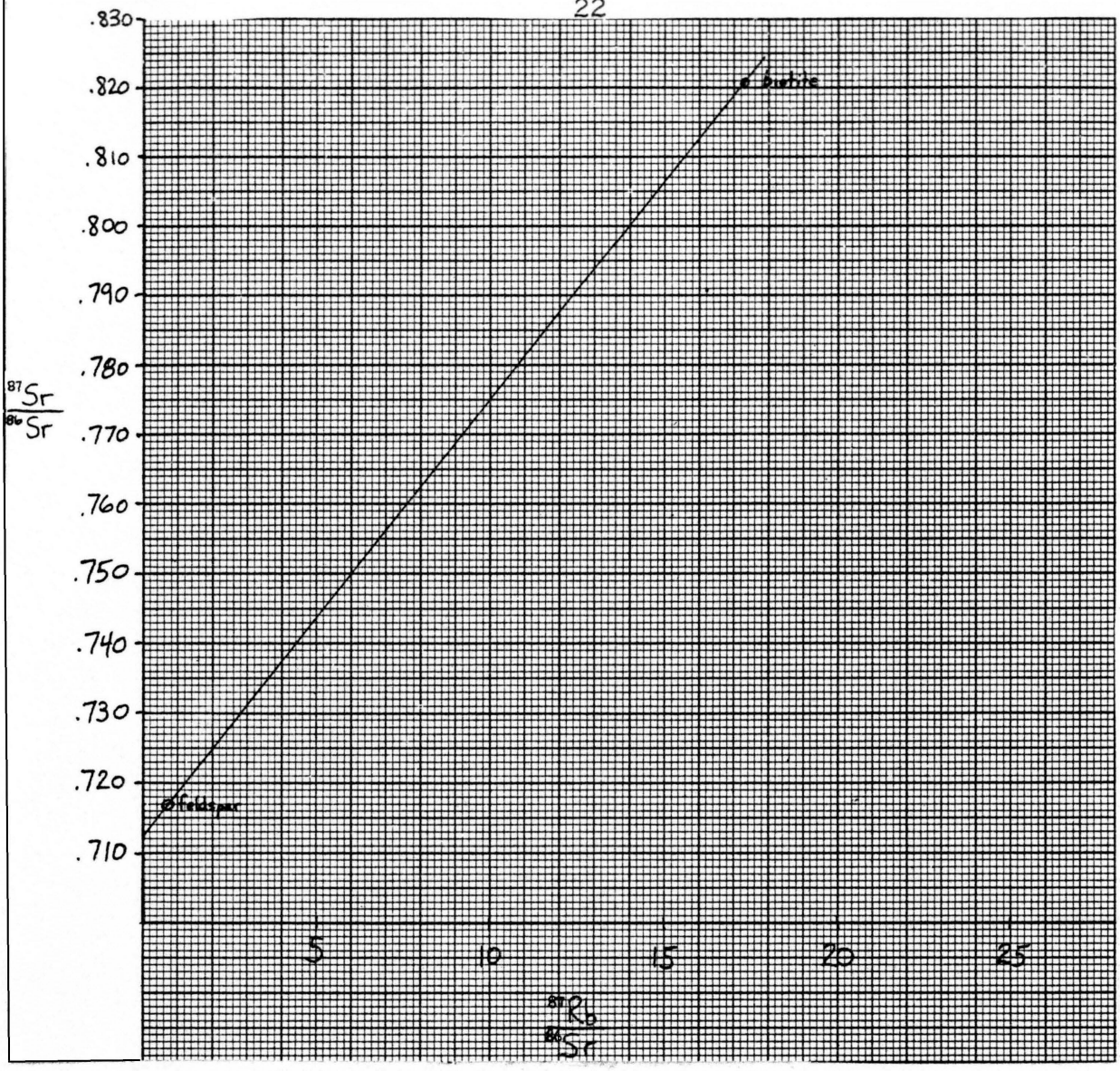


Figure 4

This graph is a mineral isochron, and from the slope of the line, the age of metamorphism may be determined.

Using the slope of this mineral isochron, we can solve for t_m, the time at which the biotite and feldspar last had the same $^{87}Sr/^{86}Sr$ ratio, which would be the time of closure following metamorphism (Figure 5).

$$\text{slope} = .00629972 = (e^{\lambda t} - 1)$$

$$t = \frac{1}{\lambda} \ln 1.00629972$$

$$= 4.4225 \times 10 \text{ y.} \approx 442.3 \text{ m.y.}$$

Using the slope of the mineral isochron, we can calculate the exact $^{87}Sr/^{86}Sr$ value of the biotite and feldspar at t= 442.3 m.y. ago. By solving equation 1 for $\left(^{87}Sr/^{86}Sr\right)_o$ we obtain:

$$\left(\frac{^{87}Sr}{^{86}Sr}\right)_o = \frac{^{87}Sr}{^{86}Sr} - \frac{^{87}Rb}{^{86}Sr}\left(e^{\lambda t} - 1\right)$$

$$= .82153 - 17.32662\left(0.00629972\right) = .71237$$

This value could be obtained using the feldspar data as well as the biotite data, since we know that at that time they had identical $^{87}Sr/^{86}Sr$ ratios. This value is in agreement with the y-intercept of Figure 4.

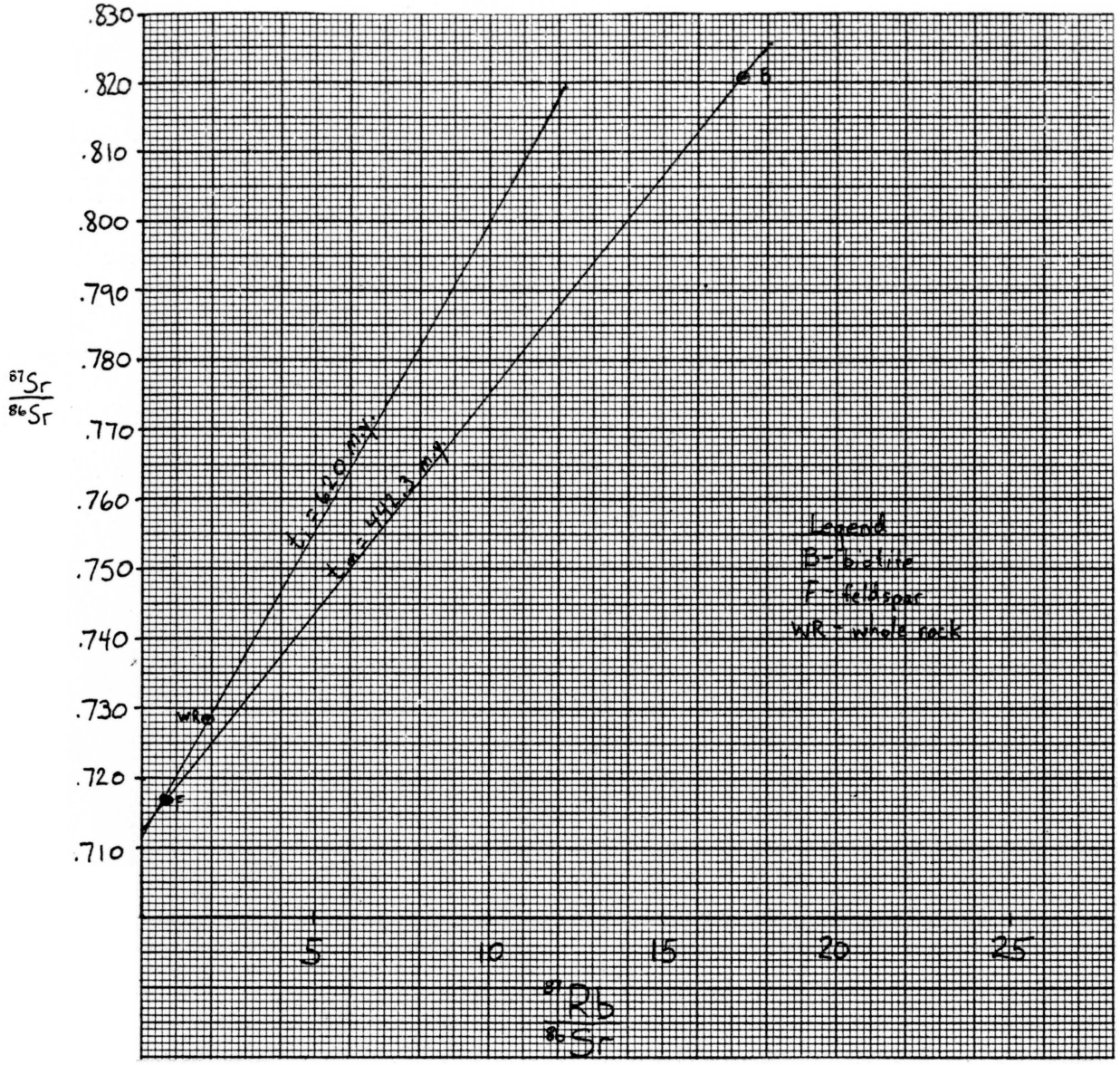


Figure 5

The difference in slopes between the mineral isochron and the whole rock isochron reflects an interval of time between initial crystallization and closure following metamorphism.

Conclusion

From the interpretation of the data obtained in this study, I cannot confirm the 846 m.y. age of crystallization for the Lonely Ridge Granodiorite.

The Lonely Ridge Granodiorite crystallized approximately 620 million years ago and was later subjected to a period of thermal metamorphism accompanied by intense cataclastic deformation. The assumption was made that the whole rock remained a closed system with respect to Rb and Sr and therefore the concentrations of these elements in the rock remained constant. The minerals however, did become open systems during metamorphism and could have exchanged radiogenic ^{87}Sr until they became rehomogenized and once again had the same $^{87}Sr/^{86}Sr$ ratio as the whole rock. In that case, at t= 442.3 m.y. ago, the minerals and whole rock would have had the same ratio for the last time, and would have evolved along their own strontium evolution lines at rates consistent with their $^{87}Rb/^{86}Sr$ ratios, until the present.

Since the whole rock does not plot on the mineral isochron (Figure 5), it becomes reasonable to assume that there was a lack of isotopic homogenization among the minerals. The biotite probably lost radiogenic ^{87}Sr, whereas the feldspar did not gain detectably. This is consistent with low temperature cataclastic deformation causing loss of ^{87}Sr from biotite without similar loss or gain by feldspar. If this is the case, the date obtained from the mineral isochron is meaningless, because it was based on the assumption that isotopic homogenization among

the minerals was achieved. The biotite date calculated with an assumed initial $^{87}Sr/^{86}Sr$ ratio of 0.704 would still be a good estimate of the time of metamorphism.

Acknowledgments

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